May 1, 2000

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SUBJECT: Monthly Progress Report No. 1 for the period April 1 to May 1, 2000; Contract No. 00130, "Evaluation of Emissions Durability of Off-Road LPG Engines Equipped with Three-Way Catalysts," SwRI Project No. 08.03661.

I. INTRODUCTION

Off-road equipment powered by gasoline and liquefied petroleum gas (LPG) engines over 19 kW is an important contributor to NOx and VOC emissions in the South Coast Air Basin. ARB has recently adopted emission standards for large spark-ignited engines, and the U.S. EPA is expected to adopt similar standards. However, at this time there is limited information on the durability of emission control systems in industrial applications and on the ability of manufacturers to control emissions in operating modes not represented by the test cycle. The objectives of this project are to develop additional data regarding the emissions and operation of large spark-ignited engines running on LPG, and to assess the durability of emission control systems in industrial applications.

In Task 1 of the project, SwRI was required to measure in-use engine operation parameters (load and speed) on two LPG-fueled forklift trucks fitted with closed-loop fuel control systems and three-way catalytic converters that had accumulated 4,000-6,000 hours of operation.

With the assistance of the U.S. EPA Project Manager, SwRI selected the test site and a list of potential test equipment. The details of the on-site activity and findings of SwRI personnel for the period between February 14-17 have been covered in the Field Trip Report forwarded to SCAQMD prior to the actual start date of this contract. Requirements 1.1 - 1.4 of Task 1 have been completed as described in the above interim report.

II. PROGRESS FROM MARCH 15 TO APRIL 15, 2000

A. Task 1 - Measure Engine Operation

1. Subtask 1.5 - Data Analysis

The first step of the data analysis was the validation and subsequent filtering of the logged data following the instructions of the U.S. EPA Program Manager. For this purpose, a data template was created with a segment length of 30 seconds (Figures 1 to 4). The entire data sets for both trucks were scrolled on the computer screen, visually checked for consistency, continuity and transducer drift, and the time stamps for the idle periods and cold and warm engine starts were logged.

Since the purpose of Task 1 is principally transient operation characterization, it was decided that every idle period of 20 seconds or longer would be removed from the data set by truncating all but the first and last one to three seconds. The variation in length, of one to three seconds, of the beginning and end time intervals of a 20 seconds or longer idle period was necessary to ensure a natural continuity of the logged engine data. Engine starts were also filtered out. A summary of the data filtering for the two sample populations is presented in Table 1. No "smoothing" was applied to any of the recorded parameters.

TABLE 1. LOGGED DATA SAMPLE POPULATION DETAILS

Truck No.	Raw Data Set (No. of Lines)	Filtered Data Set (No. of Lines)	% Filtered
16	50,523	34,898	30.92
29	95,910	66,871	30.27

The U.S. EPA Program Manager has asked for scatter plots and frequency distribution analysis of the main engine operating variables (engine speed, throttle position, and manifold absolute pressure). Figures 5 to 16 present the scatter plots for each truck based on filtered and unfiltered data sets. Although almost one third of the logged data was removed from each of the sample populations (data sets), there are minimal differences between the scatter plots based on filtered and unfiltered data sets. However, in the area of the plots corresponding to engine speed below 600 rpm and at zero percent throttle position, the deletion of the segments corresponding to engine starts is visible.

During the data validation process, it was observed that the throttle position transducers on both trucks had drifted from their original calibrations (0 to 100% throttle) by less than ±3 percent. The recorded values have been re-normalized using the following algorithm:

$$TPS_N = (TPS_{orig} - TPS_{\min}) / (TPS_{\max} - TPS_{\min}) \times 100$$

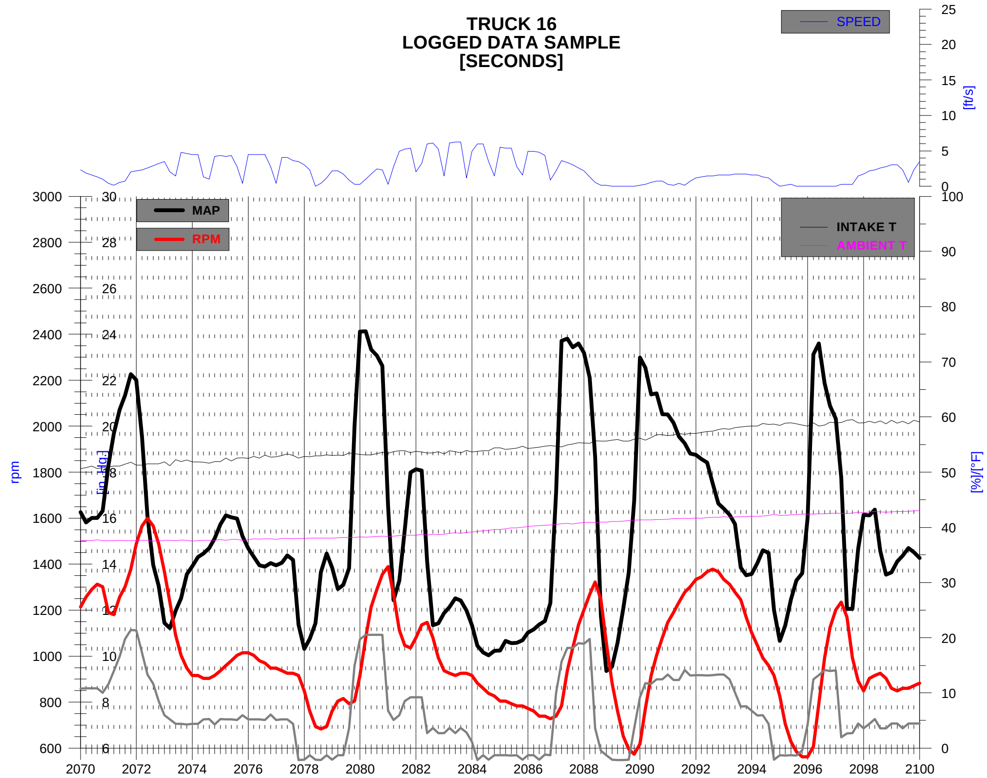

FIGURE 1. TRUCK 16, LOGGED DATA SAMPLE

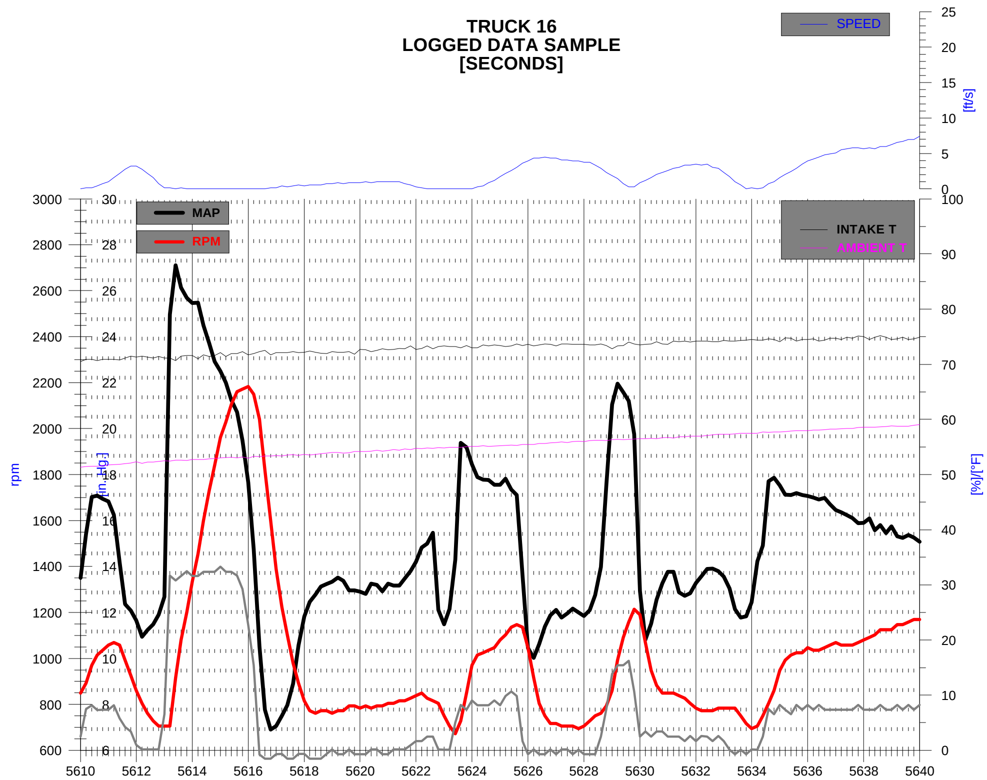

FIGURE 2. TRUCK 16, LOGGED DATA SAMPLE

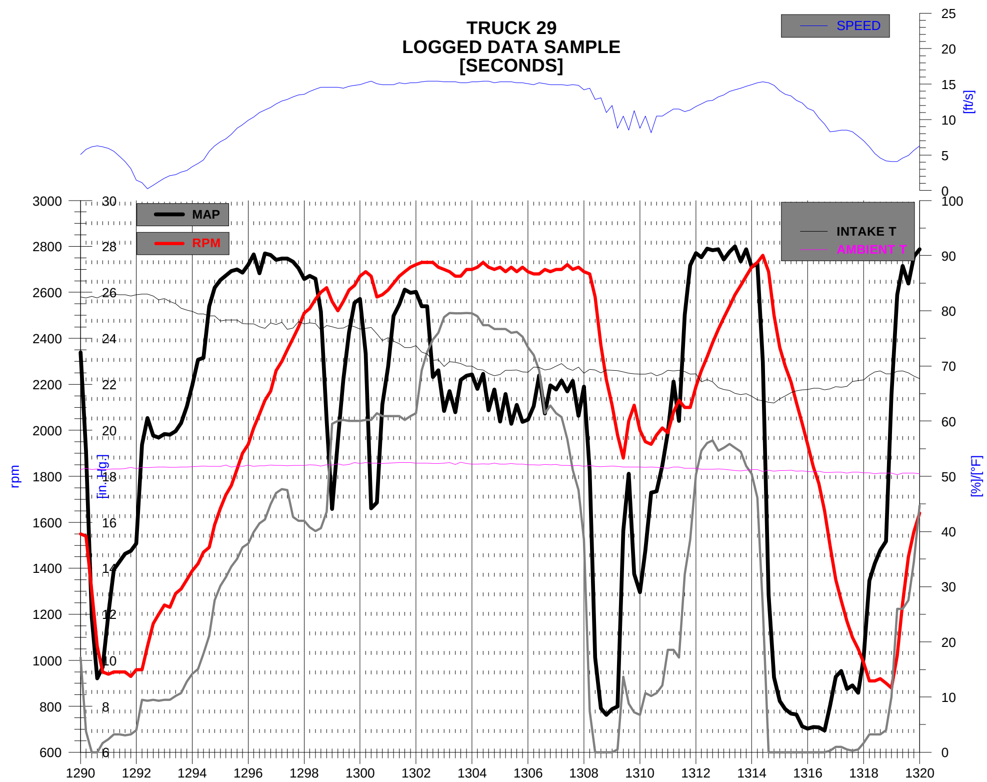

FIGURE 3. TRUCK 29, LOGGED DATA SAMPLE

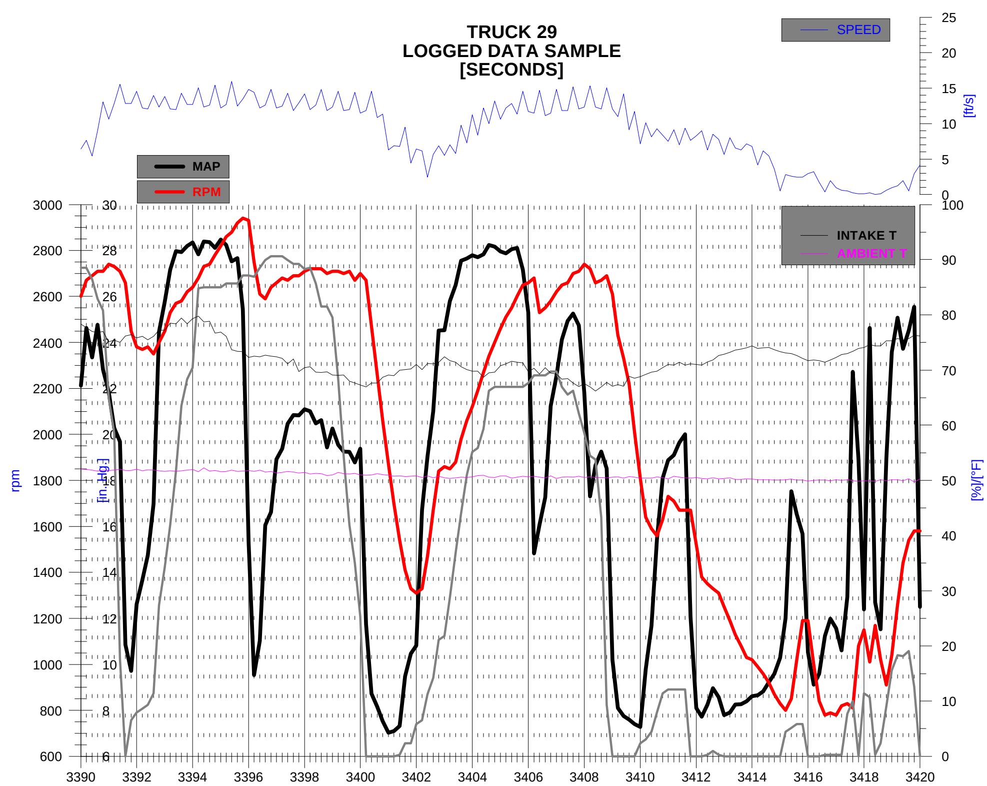

FIGURE 4. TRUCK 29, LOGGED DATA SAMPLE

<<<See file summarizing operating data for Figures 5 - 16.>>>

where: TPS_N - re-normalized throttle position
TPS_{orig} - recorded throttle position
TPS_{min} - minimum recorded throttle position (<0)
TPS_{max} - maximum recorded throttle position (>100)

For statistical analysis, each of the three parameters of interest (engine speed, throttle position, and manifold absolute pressure) was broken down into predetermined ranges, and data points were then binned in cells bounded by these ranges. The relative frequency of occurrence (RFO) for each cell was defined as the number of occurrences counted in a given cell, divided by the total number of occurrences (number of data points in the population). Therefore, the sum of the RFOs for each analyzed parameter add up to 100 percent.

Although the analysis of engine speed is based on raw, un-normalized data, a direct comparison between operating characteristics of the two different trucks is still possible since both had the same idle speed (600 rpm) and almost identical governed speed (2700 rpm). It was observed from the raw data plots that the mechanical engine speed governor on Truck 16 provided tighter and more precise control, while the pneumatic engine speed governor on Truck 29 allowed brief “over-speed” excursions to 2800 rpm.

For the frequency distribution plots in Figures 17 to 30, bars representing RFO values for the different cells are centered on the upper limit of each range.

Consistent with on-site observations, RFOs for Truck 16 show that it had a lighter duty cycle, lifting payloads of 25-30 percent of its capacity, and driven almost exclusively at closed or part throttle. This can be concluded from the fact that although both trucks have almost identical RFO numbers for the idle speed (Figures 17 to 21), Truck 16 has an RFO only about one-tenth that of Truck 29 for the 0-2 percent throttle position cell. For all other cells below 40 percent throttle position, Truck 16 has higher RFOs than Truck 29 (Figures 22 to 24). Truck 16 also has higher RFOs than Truck 29 in the low engine speed range from 800 rpm to 1500 rpm. For engine speeds above 1600 rpm and throttle positions above 40 percent, Truck 29 has higher RFOs. Results of statistical analysis of engine speed and throttle position are presented in numerical format in Tables 2 and 3.

Manifold pressure data can not be directly compared between the two trucks since they are air intake configuration-specific (Figures 25 and 26 and Table 4). However, since manifold absolute pressure is proportional to load, they appear to correlate well with the two different characteristics of the duty cycles observed for the two trucks.

A better characterization of modes of operation for the two trucks is shown in 3-D histograms of throttle position vs. engine speed (see Figures 27 to 30 and Table 5). These figures clearly show the baseline characteristics for each of the populations. These characteristics will be further analyzed to identify representative transient cycle segments.

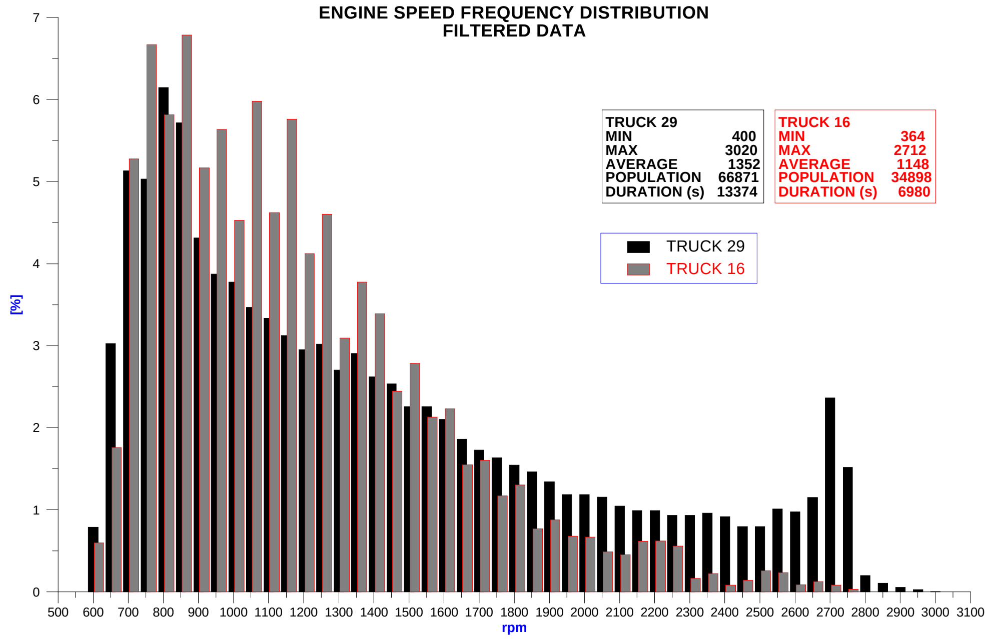

FIGURE 17. ENGINE SPEED FREQUENCY DISTRIBUTION, FILTERED DATA

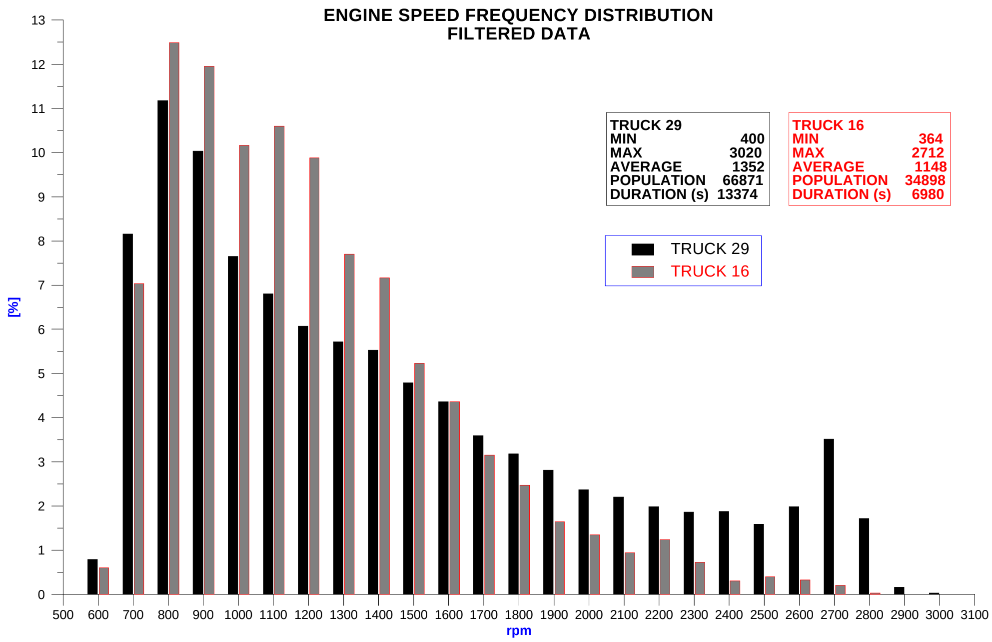

FIGURE 18. ENGINE SPEED FREQUENCY DISTRIBUTION, FILTERED DATA

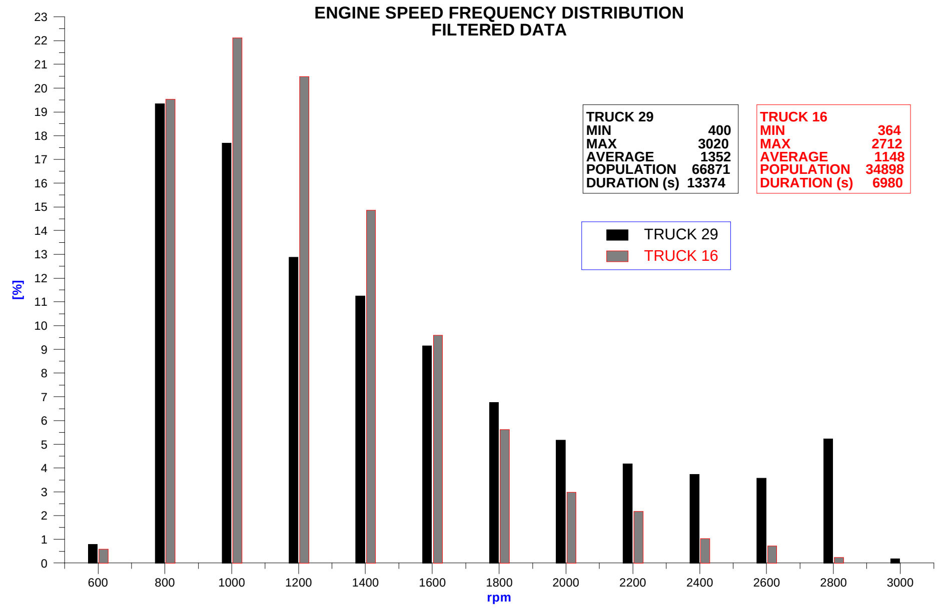

FIGURE 19. ENGINE SPEED FREQUENCY DISTRIBUTION, FILTERED DATA

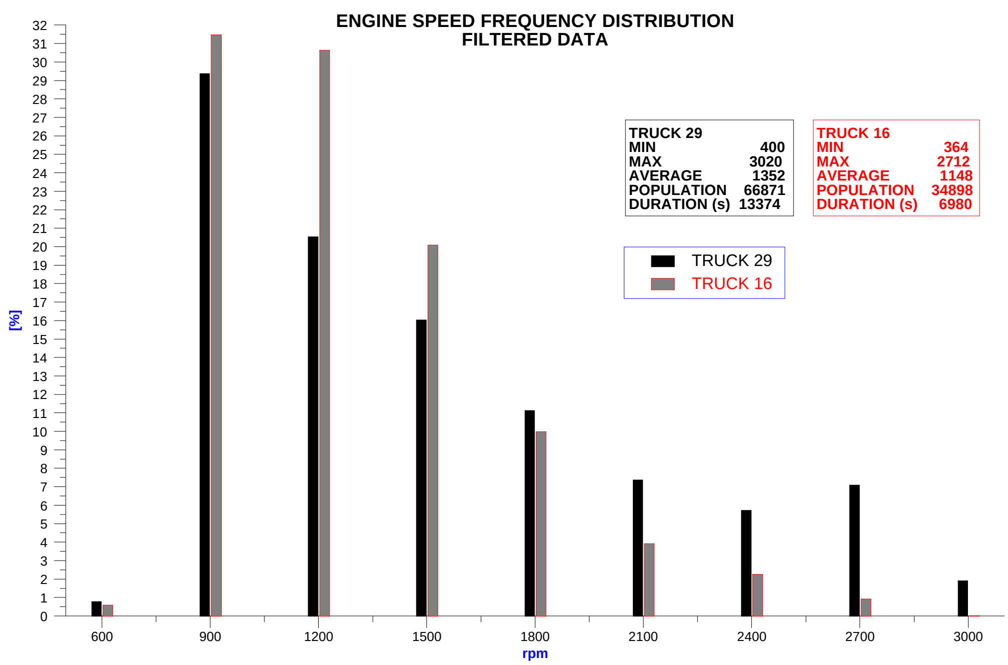

FIGURE 20. ENGINE SPEED FREQUENCY DISTRIBUTION, FILTERED DATA

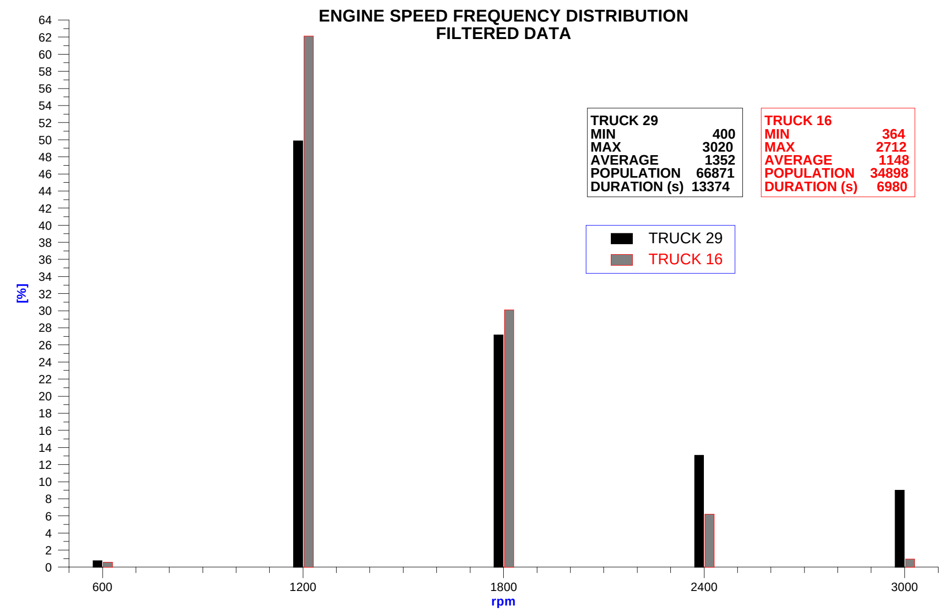

FIGURE 21. ENGINE SPEED FREQUENCY DISTRIBUTION, FILTERED DATA

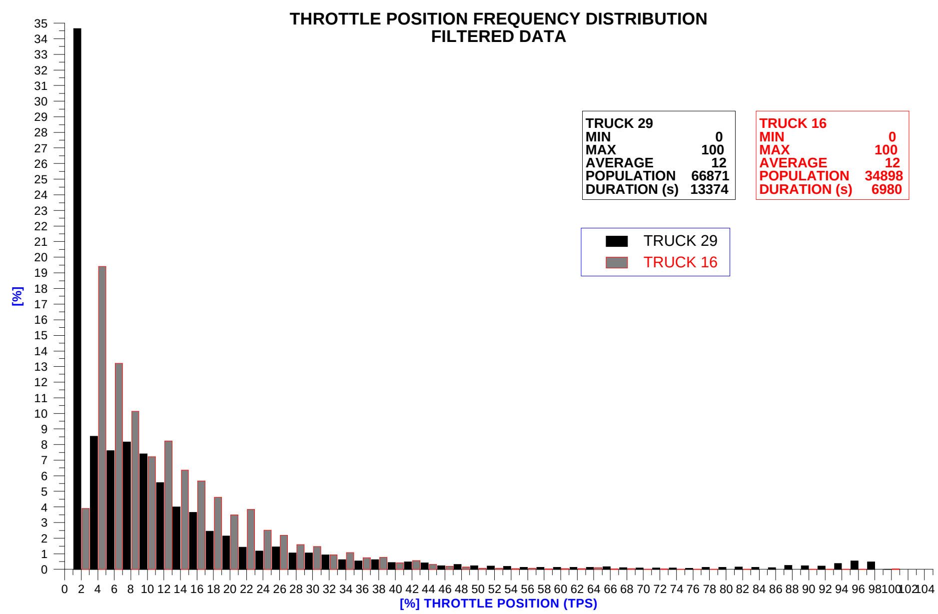

FIGURE 22. THROTTLE POSITION FREQUENCY DISTRIBUTION, FILTERED DATA

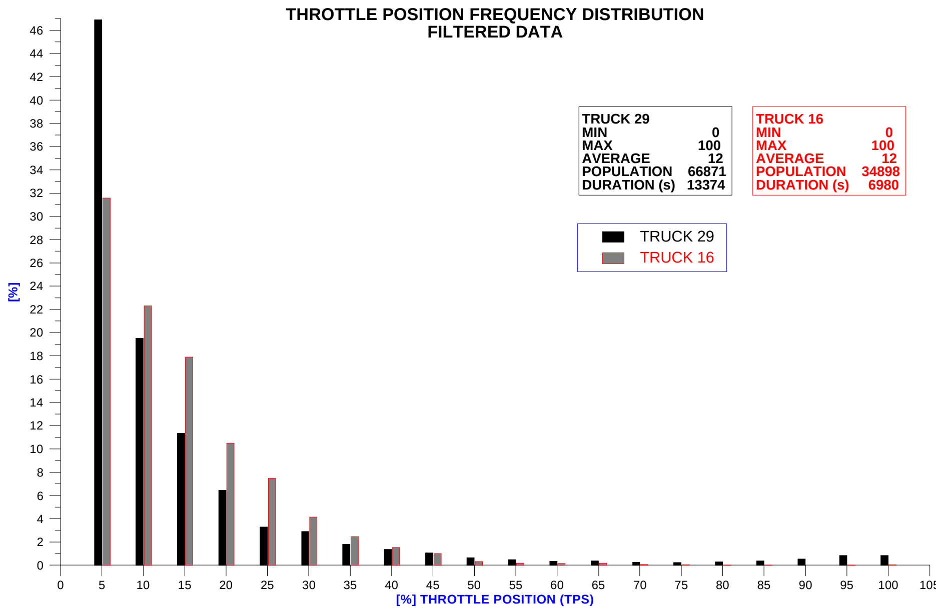

FIGURE 23. THROTTLE POSITION FREQUENCY DISTRIBUTION, FILTERED DATA

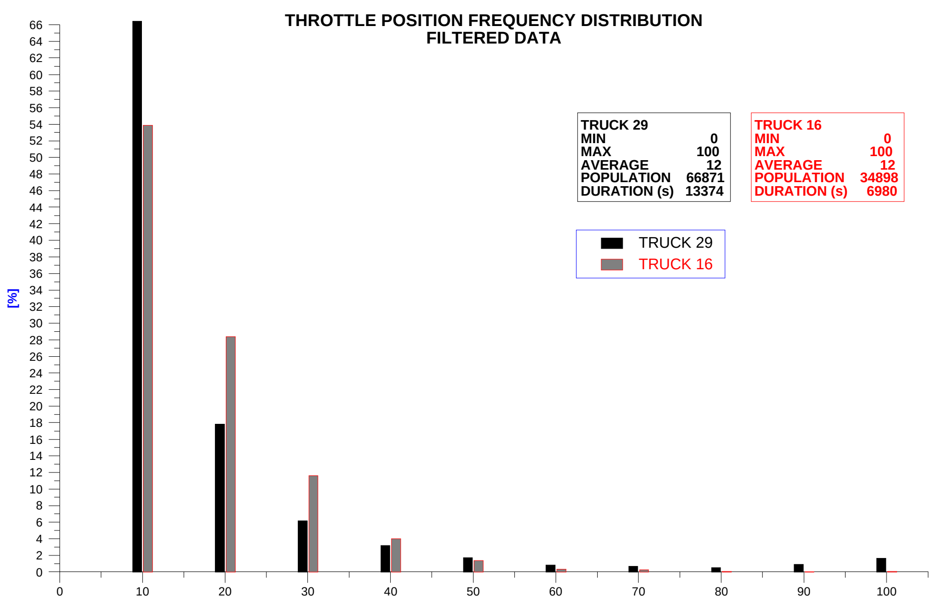

FIGURE 24. THROTTLE POSITION FREQUENCY DISTRIBUTION, FILTERED DATA

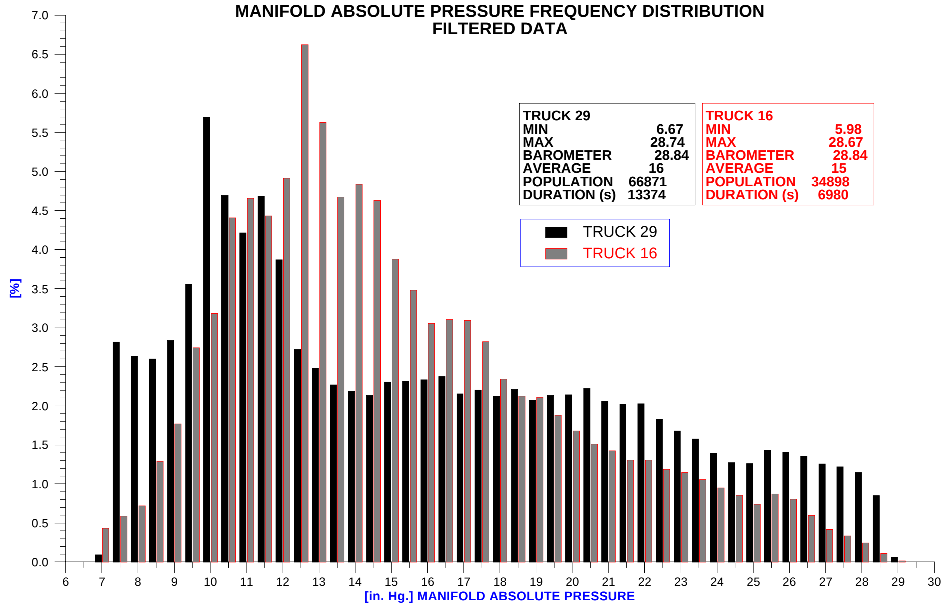

FIGURE 25. MANIFOLD ABSOLUTE PRESSURE FREQUENCY DISTRIBUTION, FILTERED DATA

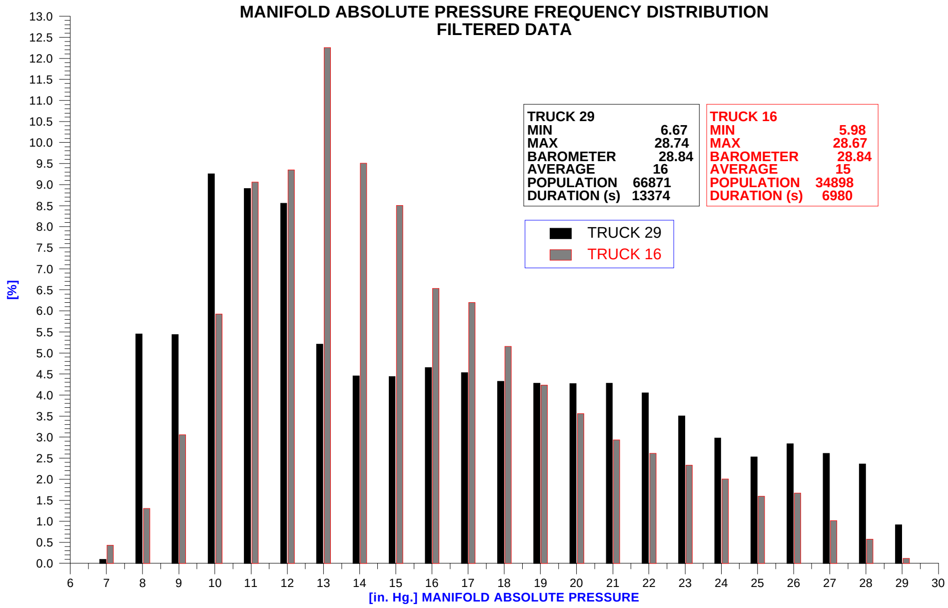

FIGURE 26. MANIFOLD ABSOLUTE PRESSURE FREQUENCY DISTRIBUTION, FILTERED DATA

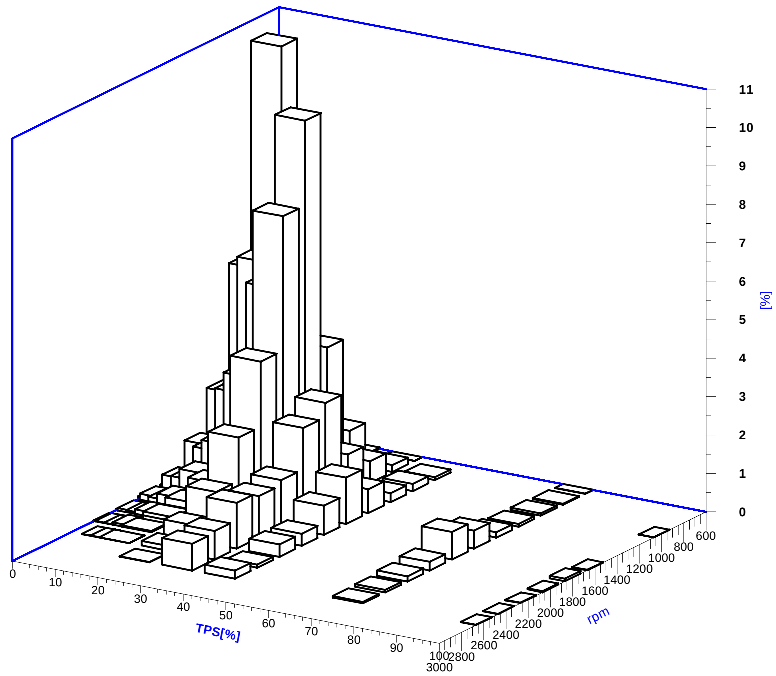

FIGURE 27. TRUCK 16, THROTTLE POSITION VS. ENGINE SPEED FREQUENCY DISTRIBUTION, FILTERED DATA - VIEW 1

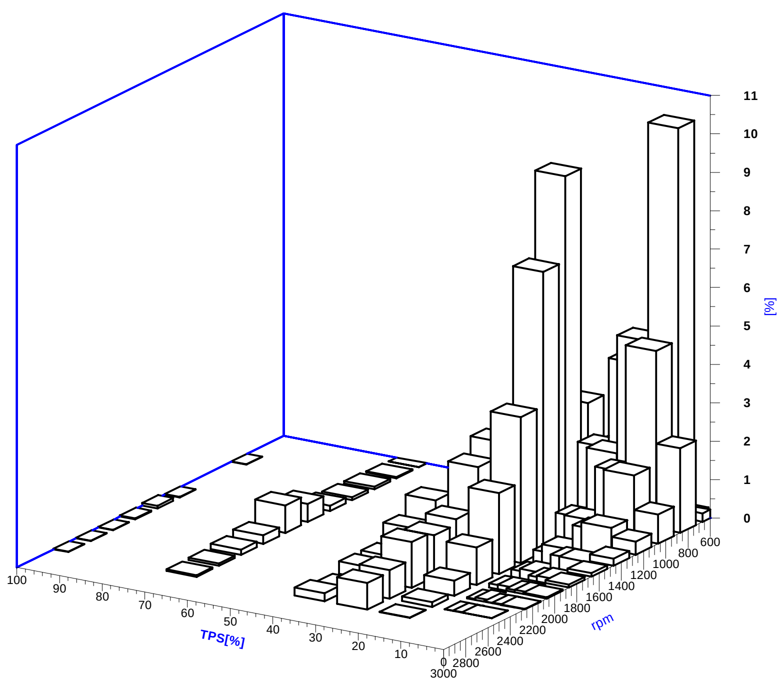

FIGURE 28. TRUCK 16, THROTTLE POSITION VS. ENGINE SPEED FREQUENCY DISTRIBUTION, FILTERED DATA - VIEW 2

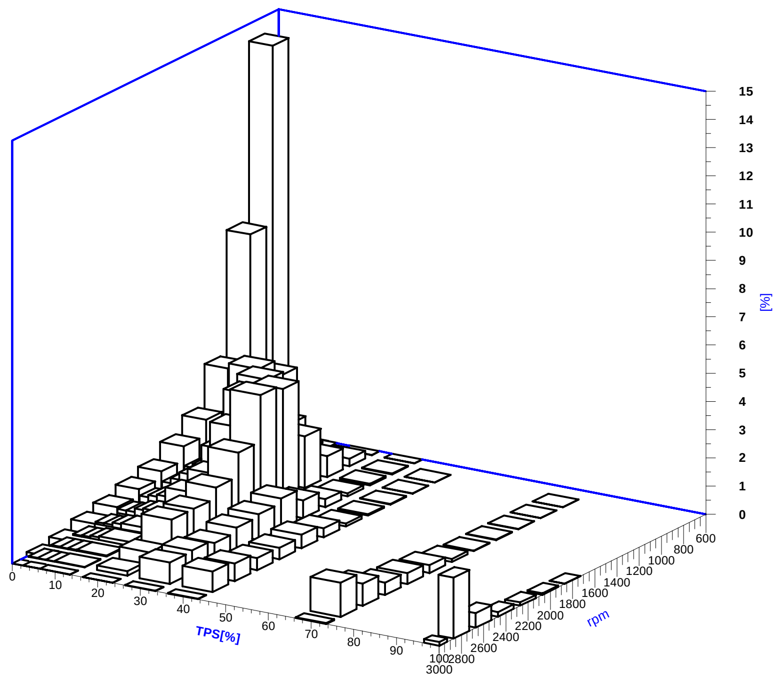

FIGURE 29. TRUCK 29, THROTTLE POSITION VS. ENGINE SPEED FREQUENCY DISTRIBUTION, FILTERED DATA - VIEW 1

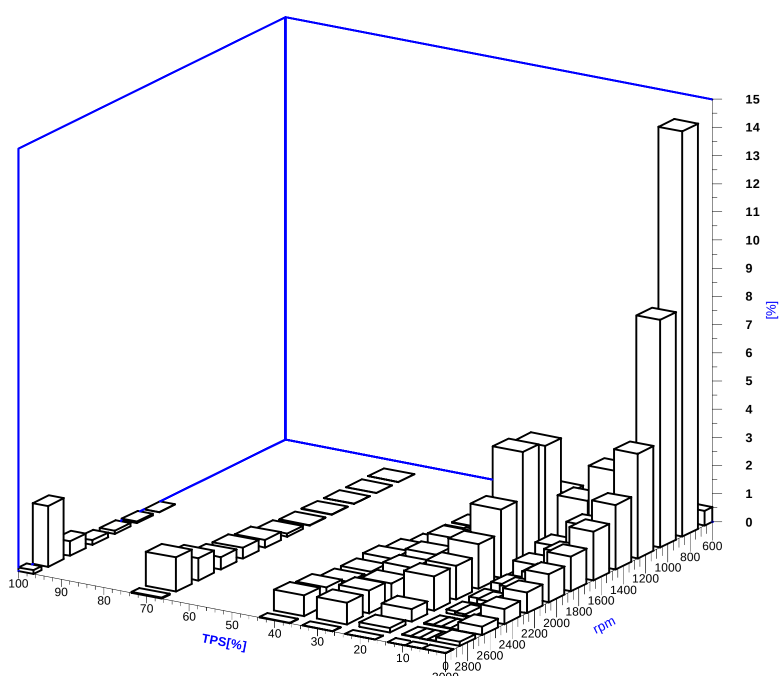

FIGURE 30. TRUCK 29, THROTTLE POSITION VS. ENGINE SPEED FREQUENCY DISTRIBUTION, FILTERED DATA - VIEW 2

TABLE 2. ENGINE SPEED FREQUENCY DISTRIBUTION, %

RPM	TRUCK 29	TRUCK16
600	0.79	0.60
650	3.03	1.76
700	5.14	5.28
750	5.03	6.67
800	6.15	5.82
850	5.72	6.79
900	4.32	5.17
950	3.88	5.64
1000	3.78	4.53
1050	3.47	5.98
1100	3.34	4.62
1150	3.13	5.76
1200	2.95	4.12
1250	3.02	4.60
1300	2.70	3.09
1350	2.91	3.78
1400	2.62	3.39
1450	2.53	2.45
1500	2.26	2.79
1550	2.26	2.13
1600	2.10	2.23
1650	1.86	1.55
1700	1.73	1.60
1750	1.64	1.17
1800	1.55	1.30
1850	1.46	0.77
1900	1.34	0.88
1950	1.19	0.68
2000	1.19	0.67
2050	1.16	0.49
2100	1.05	0.45
2150	0.99	0.62
2200	0.99	0.62
2250	0.93	0.56
2300	0.93	0.17
2350	0.96	0.22
2400	0.92	0.08
2450	0.79	0.14
2500	0.80	0.26
2550	1.01	0.23
2600	0.98	0.09
2650	1.15	0.13
2700	2.36	0.08
2750	1.52	0.03
2800	0.20	0.00
2850	0.10	0.00
2900	0.06	0.00
2950	0.03	0.00
3000	0.00	0.00

RPM	TRUCK 29	TRUCK16
600	0.79	0.60
700	8.16	7.04
800	11.18	12.49
900	10.04	11.96
1000	7.65	10.17
1100	6.81	10.60
1200	6.08	9.89
1300	5.72	7.70
1400	5.53	7.17
1500	4.79	5.23
1600	4.36	4.36
1700	3.59	3.15
1800	3.18	2.48
1900	2.81	1.65
2000	2.37	1.35
2100	2.20	0.94
2200	1.98	1.24
2300	1.86	0.72
2400	1.88	0.30
2500	1.59	0.40
2600	1.99	0.32
2700	3.52	0.21
2800	1.72	0.03
2900	0.16	0.00
3000	0.03	0.00

RPM	TRUCK 29	TRUCK16
600	0.79	0.60
800	19.34	19.53
1000	17.69	22.12
1200	12.88	20.49
1400	11.25	14.87
1600	9.15	9.60
1800	6.77	5.63
2000	5.18	2.99
2200	4.19	2.18
2400	3.74	1.03
2600	3.58	0.72
2800	5.23	0.24
3000	0.19	0.00

RPM	TRUCK 29	TRUCK16
600	0.79	0.60
900	29.38	31.49
1200	20.54	30.66
1500	16.04	20.10
1800	11.14	9.99
2100	7.38	3.94
2400	5.72	2.27
2700	7.09	0.93
3000	1.91	0.03

RPM	TRUCK 29	TRUCK16
600	0.79	0.60
1200	49.92	62.14
1800	27.18	30.09
2400	13.11	6.20
3000	9.01	0.96

	TRUCK 29	TRUCK16
MIN	400	364
MAX	3020	2712
AVG	1352	1148
POP	66871	34899
DUR	13374	6980

TABLE 3. [%] THROTTLE POSITION FREQUENCY DISTRIBUTION, %

TPS	TRUCK 29	TRUCK16
2	34.66	3.91
4	8.54	19.41
6	7.62	13.20
8	8.18	10.14
10	7.41	7.23
12	5.57	8.24
14	4.01	6.36
16	3.65	5.67
18	2.45	4.63
20	2.14	3.50
22	1.43	3.84
24	1.19	2.51
26	1.44	2.19
28	1.06	1.60
30	1.06	1.47
32	0.93	0.94
34	0.63	1.09
36	0.54	0.76
38	0.64	0.78
40	0.45	0.43
42	0.50	0.58
44	0.44	0.32
46	0.25	0.21
48	0.32	0.16
50	0.24	0.09
52	0.21	0.08
54	0.20	0.05
56	0.15	0.08
58	0.15	0.04
60	0.15	0.07
62	0.15	0.05
64	0.13	0.12
66	0.18	0.03
68	0.12	0.06
70	0.10	0.00
72	0.10	0.03
74	0.10	0.01
76	0.09	0.02
78	0.13	0.01
80	0.13	0.00
82	0.16	0.01
84	0.15	0.00
86	0.12	0.00
88	0.26	0.00
90	0.23	0.00
92	0.23	0.00
94	0.39	0.02
96	0.55	0.00
98	0.49	0.00
100	0.01	0.03

TPS	TRUCK 29	TRUCK16
5	46.89	31.59
10	19.52	22.30
15	11.35	17.90
20	6.47	10.50
25	3.28	7.47
30	2.90	4.15
35	1.81	2.46
40	1.38	1.54
45	1.06	1.03
50	0.68	0.33
55	0.49	0.17
60	0.36	0.15
65	0.40	0.18
70	0.28	0.09
75	0.24	0.05
80	0.30	0.01
85	0.37	0.01
90	0.54	0.00
95	0.83	0.03
100	0.84	0.04

TPS	TRUCK 29	TRUCK16
20	84.23	82.29
40	9.37	15.63
60	2.59	1.68
80	1.22	0.33
100	2.59	0.07

TPS	TRUCK 29	TRUCK16
10	66.41	53.89
20	17.82	28.40
30	6.18	11.62
40	3.19	4.00
50	1.74	1.36
60	0.85	0.33
70	0.68	0.27
80	0.55	0.06
90	0.92	0.01
100	1.67	0.06

	TRUCK 29	TRUCK16
MIN	0	0
MAX	100	100
AVG	12	12
POP	66871	34899
DUR	13374	6980

TABLE 4. [IN. HG.] MANIFOLD ABSOLUTE PRESSURE FREQUENCY DISTRIBUTION, %

MAP	TRUCK 29	TRUCK16
7	0.10	0.43
7.5	2.82	0.59
8	2.64	0.72
8.5	2.60	1.29
9	2.84	1.77
9.5	3.56	2.75
10	5.70	3.18
10.5	4.70	4.41
11	4.22	4.66
11.5	4.69	4.43
12	3.87	4.92
12.5	2.72	6.62
13	2.48	5.63
13.5	2.27	4.67
14	2.19	4.84
14.5	2.13	4.63
15	2.31	3.88
15.5	2.32	3.48
16	2.33	3.05
16.5	2.38	3.11
17	2.15	3.09
17.5	2.21	2.82
18	2.13	2.34
18.5	2.21	2.13
19	2.07	2.11
19.5	2.14	1.88
20	2.14	1.68
20.5	2.23	1.51
21	2.06	1.42
21.5	2.02	1.31
22	2.03	1.31
22.5	1.83	1.19
23	1.68	1.15
23.5	1.58	1.06
24	1.40	0.95
24.5	1.27	0.86
25	1.26	0.74
25.5	1.43	0.87
26	1.41	0.81
26.5	1.36	0.60
27	1.26	0.42
27.5	1.22	0.34
28	1.15	0.24
28.5	0.85	0.11
29	0.07	0.01

MAP	TRUCK 29	TRUCK16
7	0.10	0.43
8	5.46	1.31
9	5.44	3.06
10	9.26	5.93
11	8.91	9.06
12	8.56	9.35
13	5.21	12.26
14	4.46	9.51
15	4.44	8.51
16	4.65	6.54
17	4.53	6.20
18	4.33	5.16
19	4.28	4.24
20	4.28	3.56
21	4.28	2.93
22	4.05	2.61
23	3.51	2.34
24	2.98	2.01
25	2.53	1.60
26	2.84	1.68
27	2.61	1.02
28	2.37	0.58
29	0.92	0.12

MAP	TRUCK 29	TRUCK16
MIN	6.7	6.0
MAX	28.7	28.7
AVG	16	15
BAR	28.8	28.8
POP	66871	34899
DUR	13374	6980

TABLE 5. THROTTLE POSITION VS. ENGINE SPEED FREQUENCY DISTRIBUTION, %

Throttle Position, %	Engine Speed, rpm												
	600	800	1000	1200	1400	1600	1800	2000	2200	2400	2600	2800	3000	TOTAL
Truck 29														
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
2	0.52	14.39	8.08	3.71	2.28	1.73	1.23	0.99	0.74	0.54	0.30	0.15	0.00	***34.66***
4	0.18	2.75	3.36	0.89	0.50	0.34	0.22	0.14	0.08	0.03	0.02	0.02	0.00	***8.54***
6	0.05	1.08	3.04	1.68	0.63	0.52	0.30	0.15	0.08	0.04	0.02	0.01	0.00	***7.62***
8	0.02	0.54	1.59	2.95	1.35	0.78	0.38	0.28	0.16	0.09	0.03	0.01	0.00	***8.18***
10	0.01	0.28	0.81	1.69	2.24	0.96	0.70	0.33	0.20	0.13	0.03	0.02	0.00	***7.41***
20	0.01	0.26	0.74	1.83	3.90	4.07	2.42	1.57	1.20	1.21	0.44	0.16	0.00	***17.82***
30	0.00	0.03	0.06	0.11	0.28	0.63	1.09	0.92	0.83	0.67	0.80	0.76	0.01	***6.18***
40	0.00	0.00	0.01	0.02	0.04	0.11	0.32	0.48	0.41	0.43	0.63	0.73	0.02	***3.19***
70	0.00	0.00	0.00	0.00	0.02	0.02	0.11	0.27	0.38	0.44	0.79	1.21	0.03	***3.26***
100	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.11	0.17	0.51	2.16	0.13	***3.14***
TOTAL	***0.79***	***19.34***	***17.69***	***12.88***	***11.25***	***9.15***	***6.77***	***5.18***	***4.19***	***3.74***	***3.58***	***5.23***	***0.19***	
Truck 16														
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
2	0.22	2.20	0.76	0.34	0.18	0.09	0.07	0.03	0.01	0.00	0.00	0.00	0.00	***3.91***
4	0.27	10.52	5.01	2.05	0.97	0.36	0.15	0.07	0.02	0.00	0.00	0.00	0.00	***19.41***
6	0.05	4.44	5.22	2.09	0.85	0.37	0.11	0.05	0.01	0.00	0.00	0.00	0.00	***13.20***
8	0.01	0.90	4.59	2.54	1.07	0.60	0.24	0.12	0.06	0.01	0.00	0.00	0.00	***10.14***
10	0.01	0.34	2.42	2.65	1.09	0.41	0.18	0.10	0.03	0.00	0.00	0.00	0.00	***7.23***
20	0.04	0.85	3.31	9.50	7.30	3.80	2.11	0.97	0.39	0.12	0.01	0.00	0.00	***28.40***
30	0.00	0.17	0.56	1.02	2.65	2.28	1.21	1.08	1.19	0.74	0.69	0.00	0.00	***11.62***
40	0.00	0.07	0.18	0.23	0.62	1.20	0.76	0.32	0.32	0.08	0.21	0.00	0.00	***4.00***
70	0.01	0.03	0.06	0.07	0.14	0.47	0.72	0.22	0.14	0.06	0.04	0.00	0.00	***1.95***
100	0.00	0.00	0.00	0.00	0.00	0.01	0.07	0.03	0.01	0.01	0.01	0.00	0.00	***0.13***
TOTAL	***0.60***	***19.53***	***22.12***	***20.49***	***14.87***	***9.60***	***5.63***	***2.99***	***2.18***	***1.03***	***0.96***	***0.00***	***0.01***	

B. Task 2 - Collect Emission Data and Determine Emission Control System Deterioration Factors

Engines and exhaust systems from the two forklift trucks used for in-use measurements have been received at SwRI. The borrowed trucks have been replaced with equivalent rental equipment for the duration of the testing program (Task 2.1). New, replacement emission components, as well as the necessary engine diagnostic and programming tools have been procured (Task 2.2).

The engine from Truck 16, a MAZDA 4-121G, 2.0 L, has been installed in Test Cell 13 and instrumented for testing. The hydraulic pump has been removed from the engine, and a cover plate has been fabricated and installed. Without the auxiliary load from the hydraulic pump and the radiator fan, the engine idle speed has increased from the 600 rpm observed in the field, to 1650 rpm. The curb idle torque under which the engine will idle at 600 rpm was measured to be approximately 30 lb-ft. During the first calibration runs, it was observed that the engine was running lean. This contradicted the rich, on-site operation observed, which was thought to be due to a faulty oxygen sensor. Upon investigation, a crack at the base of the throttle body was discovered. This crack had become “unplugged” as a result of the steam cleaning of the engine prior to installation in the test cell. Accumulated dirt had kept the crack sealed at the time tailpipe emission measurements were taken on-site. A new throttle body has been procured, and will be installed along with a new oxygen sensor. For initial testing, an epoxy patch was applied over the crack. A torque map is being produced, which will be used to correlate in-use measured manifold absolute pressures to actual torque values.

Two of the three failed catalytic mufflers found on different trucks have also been received, and a failure mode analysis will be performed.

III. PROBLEMS

The catalytic muffler received with the engine from Truck 29 is also damaged. Although the tailpipe emission levels recorded on-site were within specification, the ceramic substrate is loose in the can, and will have to be re-canned.

IV. PLANS FOR THE NEXT REPORTING PERIOD

Task 1 - Correlate manifold absolute pressure data with torque values, normalize engine speed and torque data, and finish statistical analysis for Truck 16. Relay interim data analysis results to SCAQMD, CARB, and EPA.

Task 2 - Complete the steady state emission tests of the Truck 16 engine. Install the Truck 29 engine and begin testing. Relay interim results to SCAQMD, CARB, and EPA.

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